The Hadronic Weak Interaction: Parity Violating Asymmetry in $\vec{n} + p \to d + \gamma$

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Los Alamos National Laboratory

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High Energy Physics / Heavy Ion Physics Seminar

University of Illinois at Chicago

The NPDGamma Experiment

at Los Alamos NATIONAL LABORATORY

LANSCE (Los Alamos Neutron Science Center)

NPDGamma is under construction and will begin data collection in 2003.

Measurement of the Parity-Violating Gamma Asymmetry A_γ in the Capture of Polarized Cold Neutrons by Para-Hydrogen, $\vec{n} + p \rightarrow d + \gamma$

J.D. Bowman (Spokesperson), G.L. Greene, G.E. Hogan, J.N. Knudson, S.K. Lamoreaux, G.S. Mitchell, G.L. Morgan, C.L. Morris, S.I. Penttilä, D.A. Smith, T.B. Smith, W.S. Wilburn, and V.W. Yuan
Los Alamos National Laboratory

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T.E. Chupp, K.P. Coulter, R.C. Welsh, and J. Zerger
University of Michigan

M.S. Dewey, T.R. Gentile, D.R. Rich, and F.E. Wietfeldt
National Institute of Standards and Technology

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University of California, Berkeley

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Thomas Jefferson National Accelerator Facility

S. Ishimoto, Y. Masuda, and K. Morimoto
KEK National Laboratory, Japan

G.L. Jones
Hamilton College

F.W. Hersman, M.B. Leuschner, and V.R. Pomeroy
University of New Hampshire

S.A. Page and W.D. Ramsay
University of Manitoba and TRIUMF

E.I. Sharapov
Joint Institute for Nuclear Research, Dubna

http://p23.lanl.gov/len/npdg/

Outline

- What is NPDGamma measuring?
  Theory and some historical perspective

- Planned apparatus

- Potential systematic errors

- Test runs with small scale apparatus &
  PV (n,γ) measurements on nuclear targets

- Status & schedule

NPDGamma: $\vec{n} + p \to d + \gamma$ (2.2 MeV)

Measure parity-violating asymmetry A_γ
in capture of polarized cold n by para-H_2

Expected asymmetry $\approx 5 \times 10^{-8}$

Goal experimental error: 0.5×10^{-8}

A_γ is a clean measurement of H_π^1:

$$A_\gamma \approx -0.045 H_\pi^1$$

the most significant weak nucleon-nucleon
coupling, a fundamental quantity in low-energy
QCD and weak interaction physics

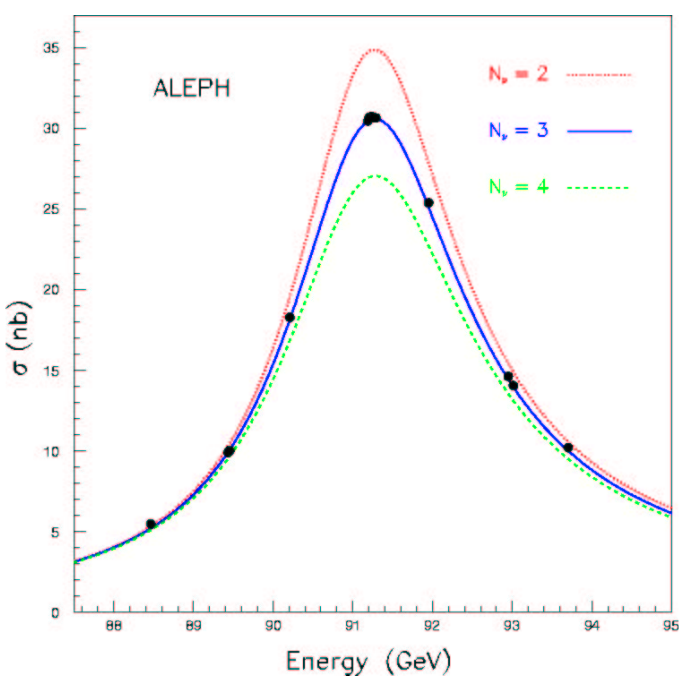
Weak Interaction

Standard model of electroweak interactions
has been extensively studied at colliders

precision measurements:

$$\begin{aligned} M_Z &= 91.1882 \pm 0.0022 \text{ GeV} \\ M_W &= 80.419 \pm 0.056 \text{ GeV} \end{aligned}$$

D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000)

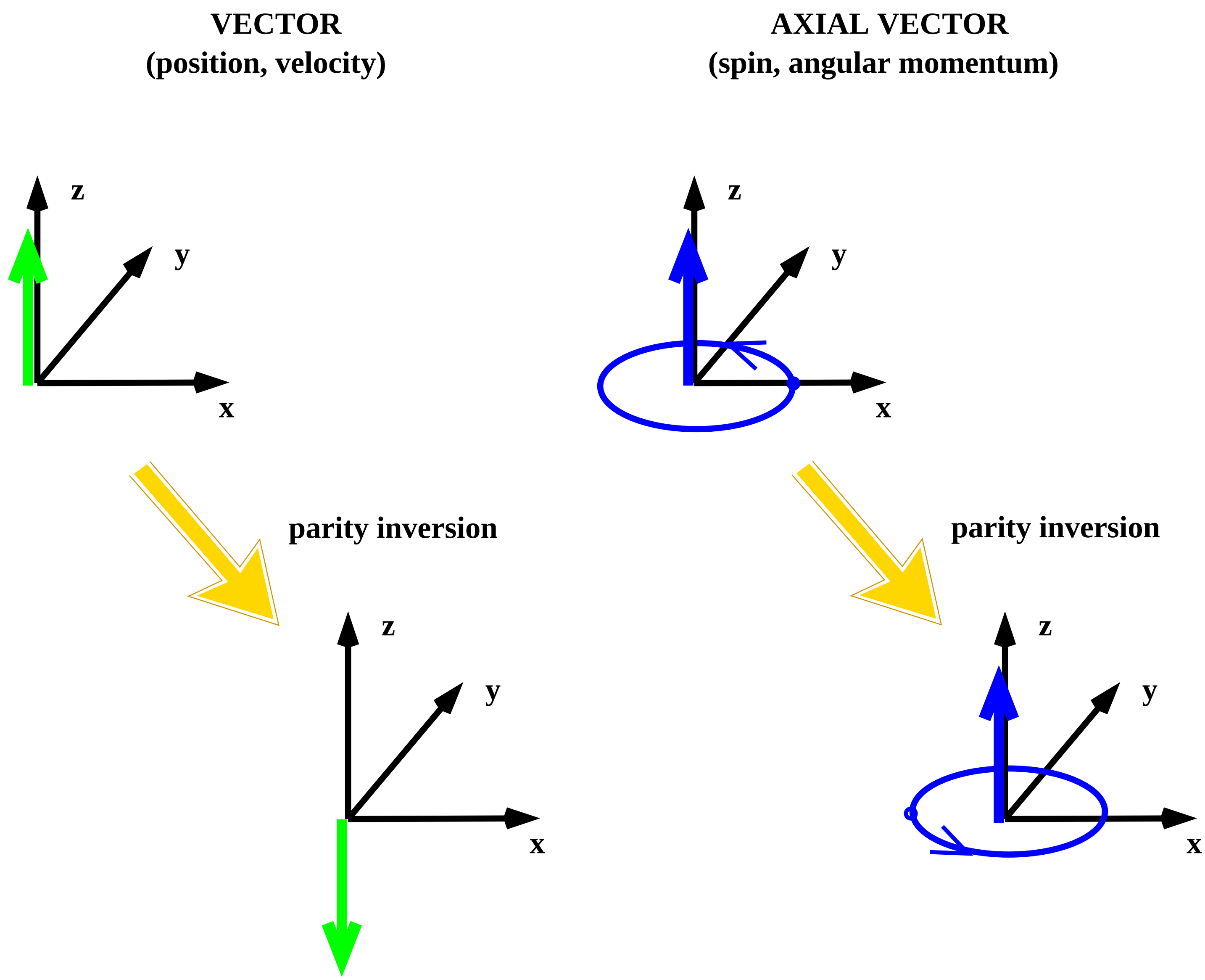


`http://alephwww.cern.ch`

well understood how quarks
and leptons interact weakly

Weak interaction: parity is not conserved

$$P(x,y,z) \longrightarrow (-x,-y,-z)$$



(Brief)

History of Parity Violation

The possibility of PV in the weak interaction was first suggested by T. D. Lee and C. N. Yang. [Phys. Rev. **104** (1956) 254.]

First seen experimentally by C. S. Wu, *et al.* in asymmetry of β emission from polarized ^{60}Co. [Phys. Rev. **105** (1957) 1413.]

Parity violation in nuclear transitions first seen by V. M. Lobashov, *et al.* in circular polarization of the 482 keV γ ray from ^{181}Ta: $P_\gamma = -6 \pm 1 \times 10^{-6}$. [Phys. Lett. **25B** (1967) 104.]

$\rightsquigarrow$ first measurement of hadronic PV

Range of Z, W^+, W^- bosons is 0.002 fm

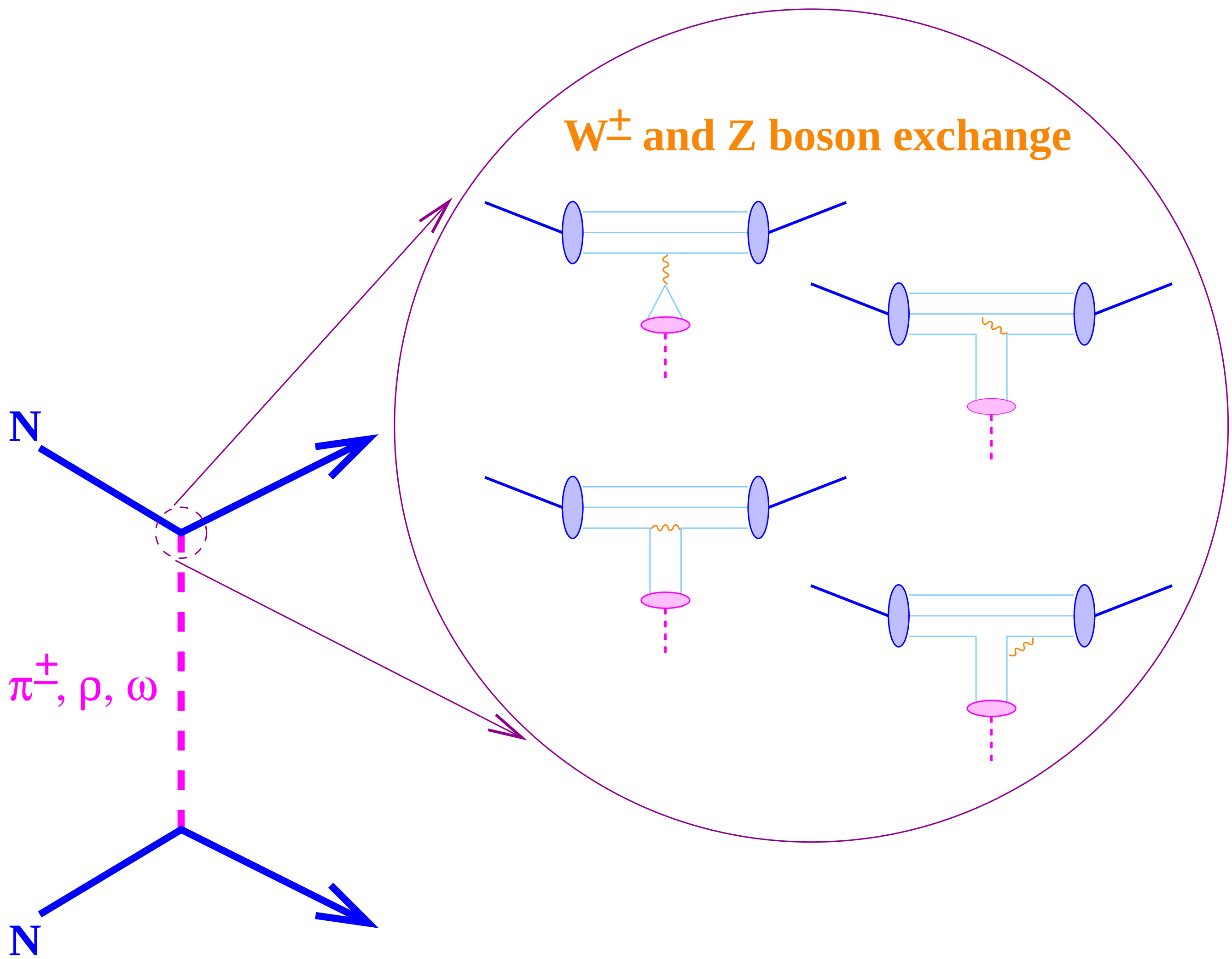
But nucleon interactions take place
on a scale of 1 fm (short range repulsion)

$\rightsquigarrow$ model the weak force interaction between
nucleons and hadrons as meson exchange

At low energies ($<$ 300 MeV)
mesons are the appropriate degree of freedom

Meson exchange model is a successful picture of strong interactions between nucleons (describes to a few % n-p/p-p scattering cross-sections)

N-N weak interaction modeled as meson exchange with one strong PC vertex, one weak PV vertex

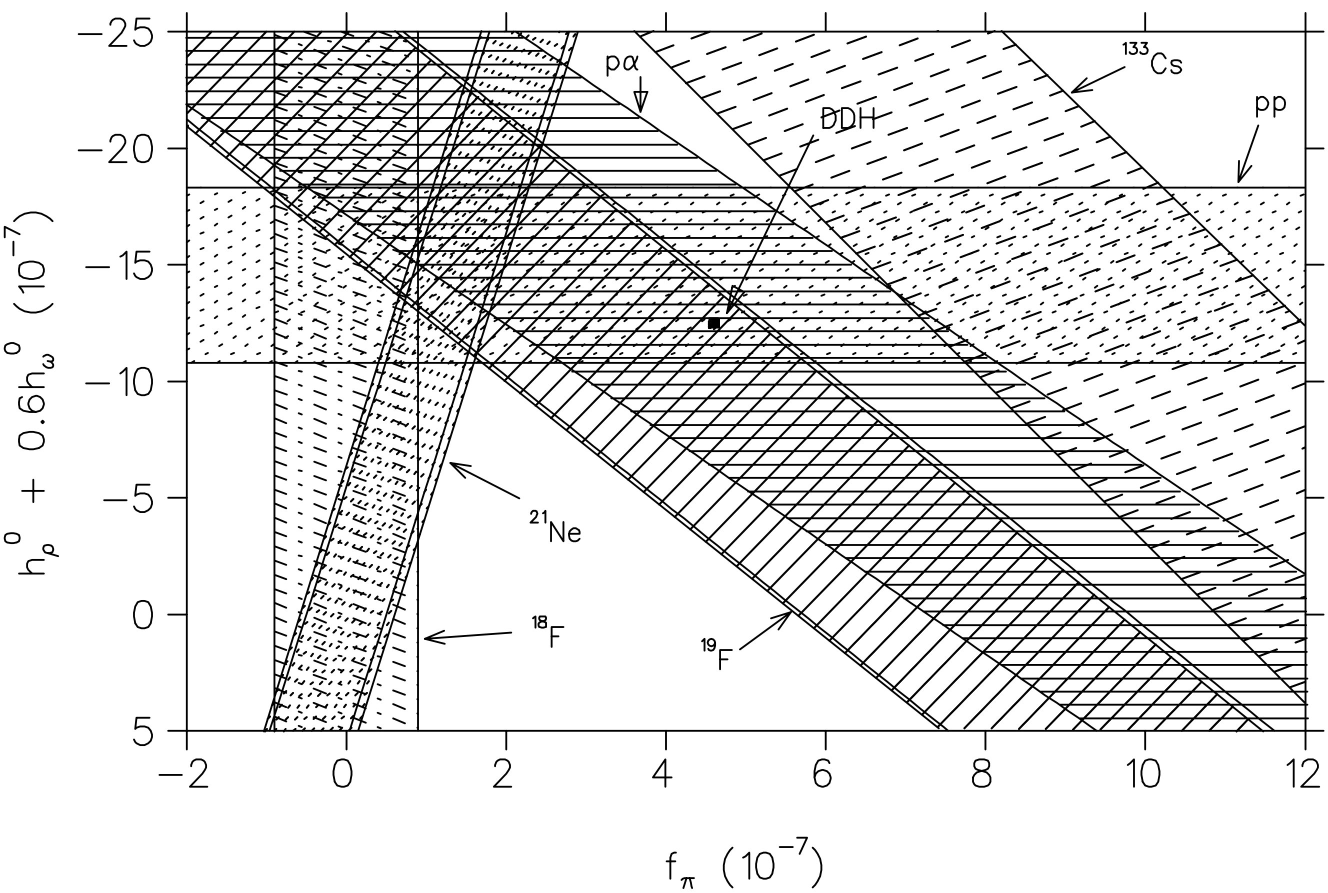


The weak PV couplings –

$$H_\pi^1,\ H_\rho^0,\ H_\rho^1,\ H_\rho^{1'},\ H_\rho^2,\ H_\omega^0,\ H_\omega^1$$

–measured in various combinations by a variety of observables

Experimental Constraints on Weak N-N Couplings



[Plot from review article: W. van Oers, Nucl. Phys. **A684** (2001) 266.]

$$\text{N. B.}\quad f_\pi = \frac{\sqrt{32}}{g_{\pi \mathrm{NN}}} \times H_\pi^1$$

N-N Observables

A_z^{pp}(45 MeV) $\approx$

$$-0.053\left(H_\rho^0 + H_\rho^2/\sqrt{6}\right) - 0.016\left(H_\omega^0 + H_\omega^1\right)$$

PSI, Bonn, LANL

A_z^{pp}(221 MeV) $\approx$

$$0.028\left(H_\rho^0 + H_\rho^2/\sqrt{6}\right)$$

TRIUMF 497, 761

$A_\gamma^{np} \approx$

$$-0.045 H_\pi^1$$

Under Construction — LANL

$P_\gamma^{np} \approx$

$$0.022 H_\rho^0 + 0.043 H_\rho^2/\sqrt{6}$$

Letter of Intent — JLab (LOI 00-002, PAC 17)

$\phi_{pnc}^{np} \approx$

$$-1.31 H_\pi^1 - 0.23 H_\rho^0 - 0.25 H_\rho^2 - 0.23 H_\omega^0$$

Under Development — NIST, ILL

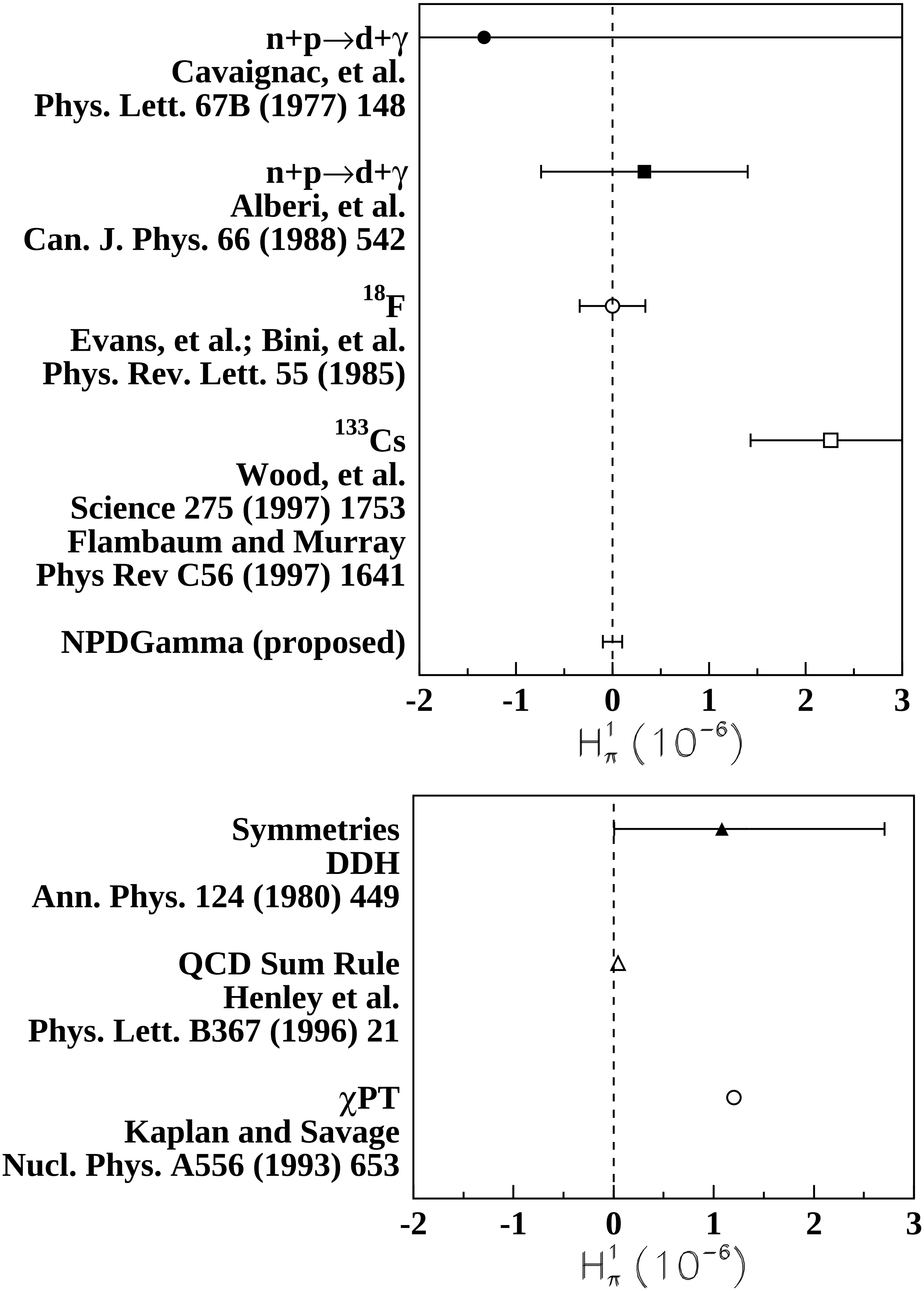
DDH

The benchmark theoretical calculations for nucleon-nucleon parity violation.

B. Desplanques, J. F. Donoghue, B. R. Holstein, Annals of Physics **124** (1980) 449.

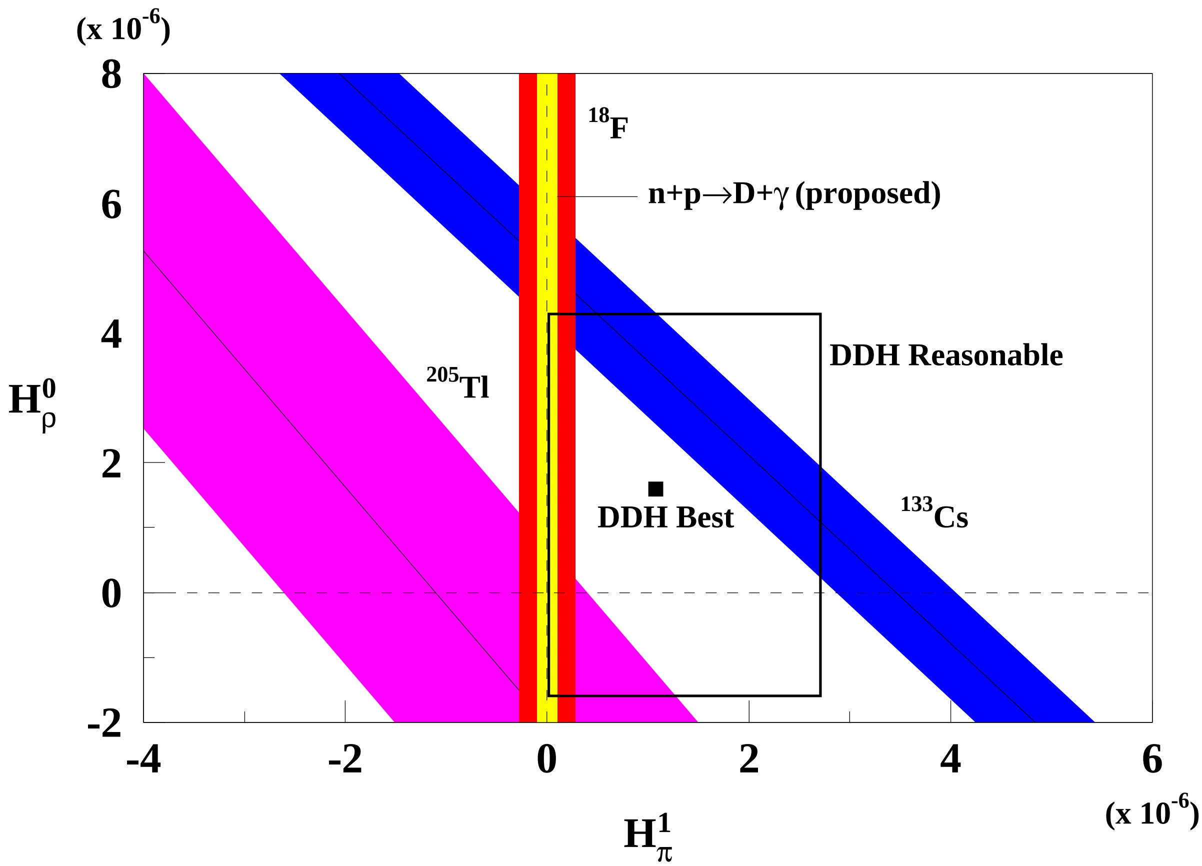
DDH estimated the weak PV couplings based on:

quark model
SU(6) symmetry
hyperon nonleptonic decays



n+p→d+γ
Cavaignac, et al.
Phys. Lett. 67B (1977) 148
n+p→d+γ
Alberi, et al.
Can. J. Phys. 66 (1988) 542
18F
Evans, et al.; Bini, et al.
Phys. Rev. Lett. 55 (1985)
133Cs
Wood, et al.
Science 275 (1997) 1753
Flambaum and Murray
Phys Rev C56 (1997) 1641
NPDGamma (proposed)
-2 -1 0 1 2 3
H1π (10-6)
Symmetries
DDH
Ann. Phys. 124 (1980) 449
QCD Sum Rule
Henley et al.
Phys. Lett. B367 (1996) 21
χPT
Kaplan and Savage
Nucl. Phys. A556 (1993) 653
-2 -1 0 1 2 3
H1π (10-6)

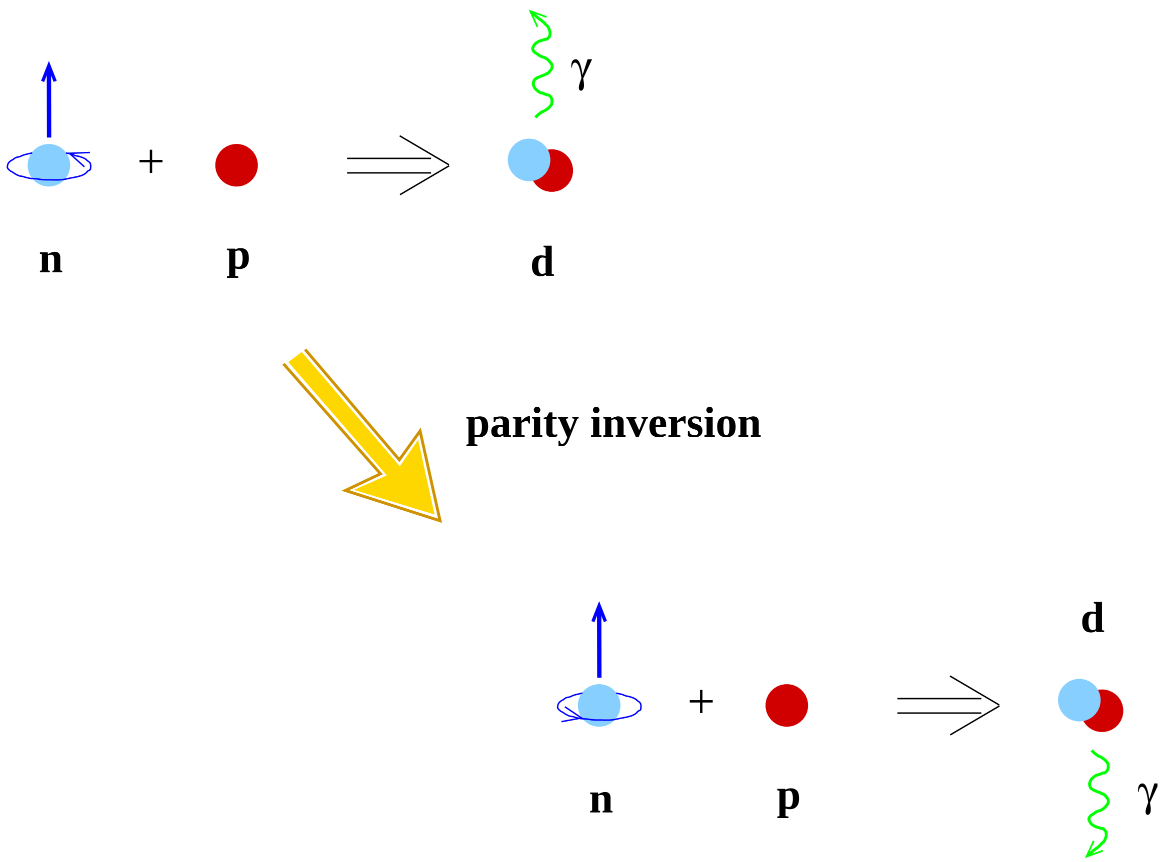
Weak Couplings from ^{18}F, ^{133}Cs, and ^{205}Tl



W.S. Wilburn and J.D. Bowman, Phys. Rev. **C57** (1998), 3425.

NPDGamma will provide a measurement with improved statistical precision compared to ^{18}F results, with no uncertainties from many-body calculations or nuclear structure effects

NPDGamma will measure A_γ, the parity-violating asymmetry in the distribution of emitted γ



If the γ rates differ for the two cases, i.e. more γ's emitted up than down, then parity is violated

The capture process is dominated by the parity-conserving strong force, so the gamma asymmetry is very small

Why is there parity violation in $\vec{n} + p \rightarrow d + \gamma$?

The weak force allows an interference between S and P states, which are states of opposite parity, in the capture of the neutron by the proton. (An interference between M1 and E1 amplitudes.)

The expected PV asymmetry is small

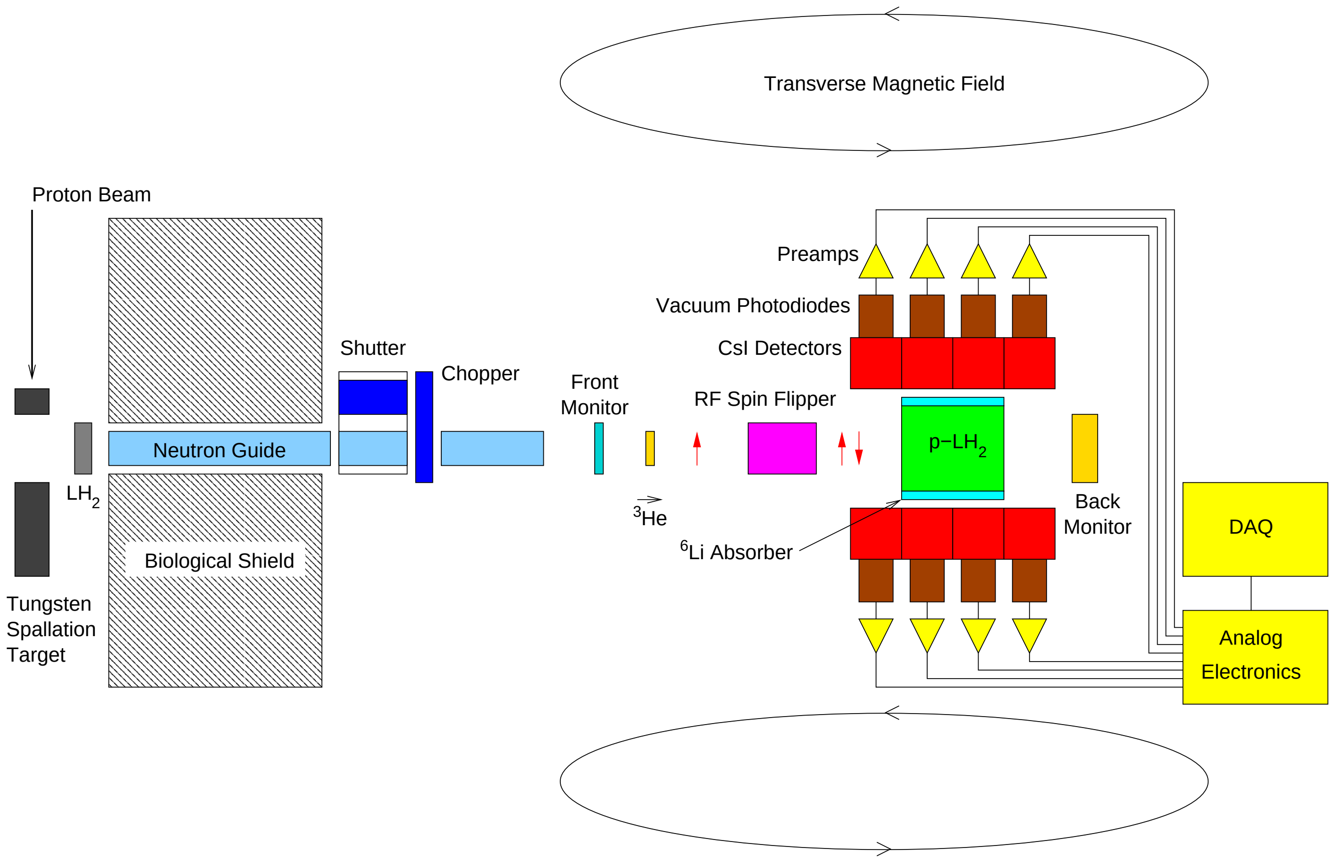
estimated size $G_F \times m_\pi^2 \approx 10^{-7}$

Experimentally:
measure asymmetry between up and down γ rates

$$A_\gamma^{np} \approx -0.045 H_\pi^1$$

Clean interpretation in terms of only one coupling constant. (Rare and fortunate.)

NPDGamma Experimental Setup



NPDGamma is a fully funded experiment ($4.8M, primarily DOE)

Experiment: measure the directional asymmetry

$$A_\gamma$$

of 2.2 MeV γ-rays emitted upon polarized neutron capture in the para-hydrogen target.

NPDGamma Vital Statistics

LANSCE accelerator:

$\frac{1}{2}$ mile long, 80 kW, 800 MeV H^-

The LANSCE accelerator is the world's highest power linear proton accelerator.

PSR operates at 20 Hz, delivers up to 100 μA of protons to W spallation target at Lujan Center.

The peak neutron flux at the Lujan Center is the highest in the world.

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neutron beam polarized by ^{3}He spin filter
neutron polarization: 0.50 $\rightarrow$ 0.95

FP12 peak flux: 8×10^7 n/ms (@ 8 meV = 3.2 Å)

event rate per 20 Hz pulse: 1.1×10^8

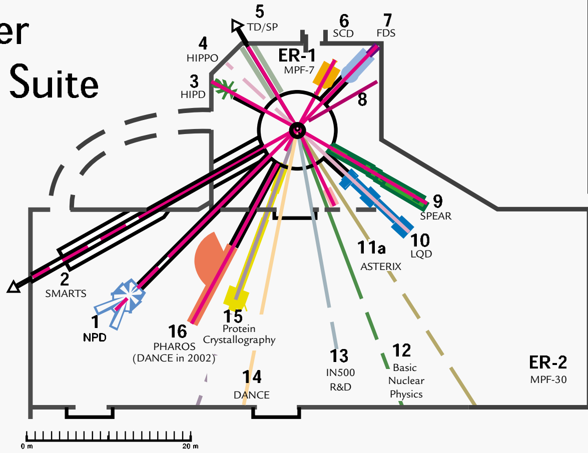
γ's from neutron capture detected by CsI(Tl) and photodiode detector array operating in current mode

gain provided by low-noise solid-state preamplifiers

run time: 2 $\times$ 6 months @ 75% live

Overview

Lujan Center Instrument Suite



Moderators
1, 2, 16: high-resolution H_2O decoupled
3, 4, 5: high-intensity H_2O decoupled
6, 7, 8: high-intensity H_2O decoupled
9, 10, 11: ℓH_2 @ 20 K partially coupled
12, 13: ℓH_2 @ 20 K coupled
14, 15: H_2O coupled

FP1 **Neutron Powder Diffractometer (NPD)** allows for studies of complex structures, internal strain measurements, and phase transformation.
Don Brown, 505-667-7904, dbrown@lanl.gov

FP2 **Spectrometer for Materials Research at emperature and Stress (SMAR S)** will allow measurements of spatially resolved strain-fields, phase deformation and load transfer in composites, the evolution of stress during temperature (or pressure) fabrication, and the development of strain during reactions (such as reduction, oxidation, or other phase transformations).
Mark Bourke, 505-665-1386, bourke@lanl.gov

FP3 **High Intensity Powder Diffractometer (HIPD)** is designed to study the atomic structure of materials that are available only in polycrystalline or noncrystalline forms.
Robert Von Dreele, 505-667-3630, vondreele@lanl.gov

FP4 **High-Pressure-Preferred Orientation (HIPPO)** instrument is a new high-intensity powder diffractometer for high-pressure and texture measurements.
Kristin Bennett, 505-665-4047, bennett@lanl.gov and Robert VonDreele, 505-667-3630, vondreele@lanl.gov

FP5 **FP5** is used to study the Doppler shift and broadening of low-energy nuclear resonances in materials under extreme conditions and for structural studies using transmission Bragg diffraction.
Vincent Yuan, 505-667-3939, vyuan@lanl.gov

FP6 **Single Crystal Diffractometer (SCD)** has been used to study the structure of organometallic molecules, unique binding of H_2 crystal structure changes at solid-solid-phase transitions, magnetic spin structures, twinned or multiple crystals, and texture.
Yusheng Zhao, 505-667-3886, yzhao@lanl.gov

FP7 **Filter Difference Spectrometer (FDS)** is designed to determine energy transferred to vibrational modes in a sample by measuring the changes in the energies of the scattered neutrons.
Juergen Eckert, 505-665-2374, juergen@lanl.gov

FP9 **Surface Profile Analysis Reflectometer (SPEAR)** is used with an unpolarized neutron beam to study solid/solid, solid/liquid, solid/gas, and liquid/gas interfaces.
Greg Smith, 505-665-2842, gsmith@lanl.gov and Jaroslaw Majewski, 505-667-8840, jarek@lanl.gov

FP10 **Low-Q Diffractometer (LQD)** is designed to study structures with dimensions in the range from 10 to 1000 Å. It measures a broad Q-range in a single experiment without physical changes to the instrument.
Rex Hjelm, 505-665-2372, hjelm@lanl.gov

FP11a **AS ERIX** will provide a polarized neutron beam for studies of magnetic materials, using reflectometry and diffraction, and includes application of high magnetic fields.
Mike Fitzsimmons, 505-665-4045, fitz@lanl.gov

FP12 **FP12** will be used for a fundamental nuclear physics experiment to precisely measure the asymmetry of the emission of gamma rays from the capture of polarized neutrons by protons.
David Bowman, 505-667-7633, bowman@lanl.gov

FP13 **IN500** is a protoype instrument under development employing novel techniques to enhance inelastic cold-neutron spectroscopy at spallation neutron sources.
Margarita Russina, 505-667-8841, russina@lanl.gov
Ferenc Mezei, 505-667-7633, mezei@lanl.gov

FP14 **Detector for Advanced Neutron Capture Experiments (DANCE)** will be used for the study of neutron capture on radioactive nuclei in support of the stockpile stewardship program and for nuclear astrophysics.
John Ullmann, 505-667-2517, ullmann@lanl.gov

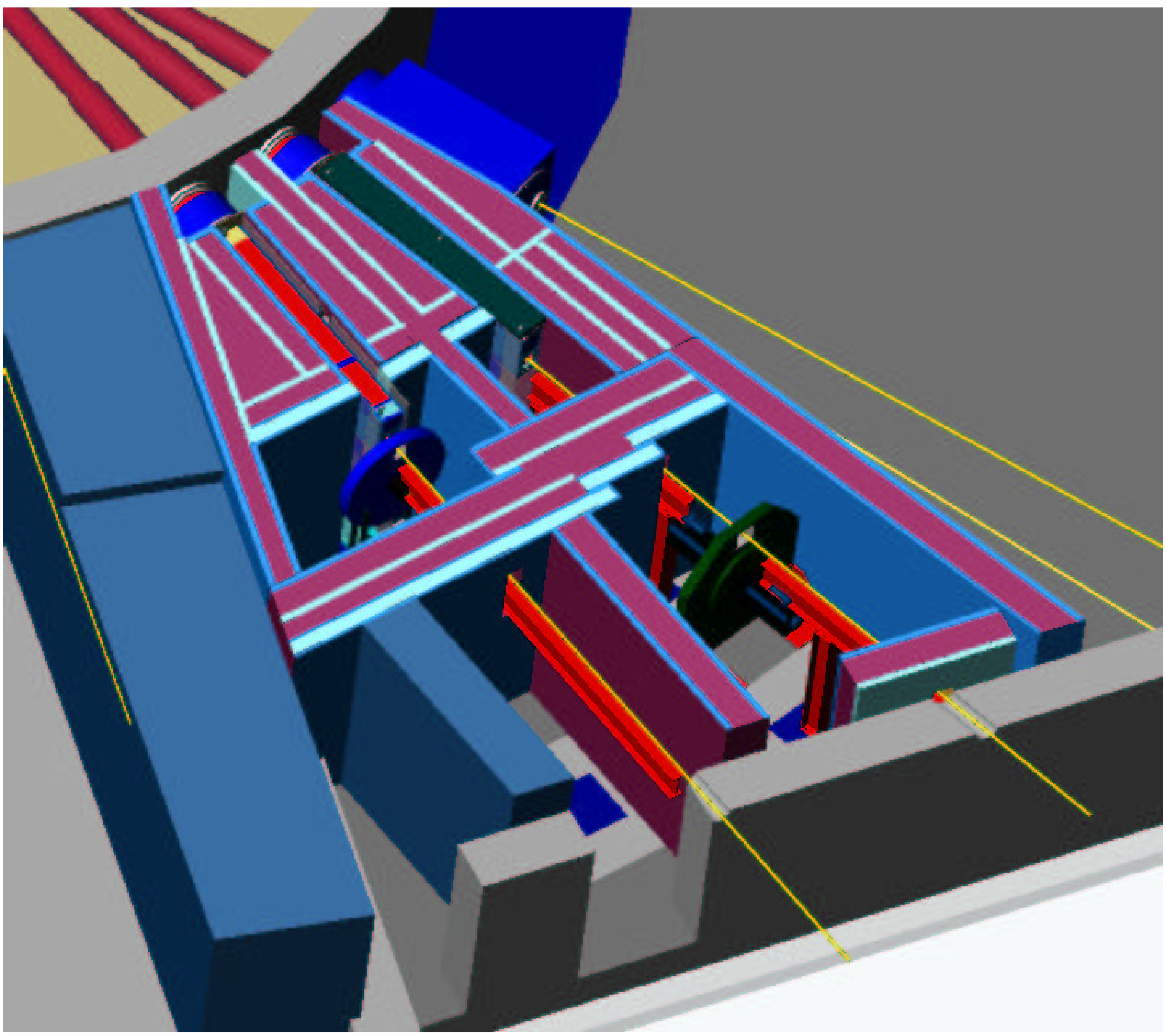
FP15 **Protein Crystallography Station (PCS)** is a single-crystal diffractometer designed for structure determinations of large biological molecules.
Paul Langan, 505-665-8125, langan_paul@lanl.gov
Benno Schoenborn, 505-665-2033, schoenborn@lanl.gov

FP16 **PHAROS** is a high-resolution chopper spectrometer designed for studies of Brillouin scattering, magnetic excitations, phonon densities of state, crystal-field levels, and chemical spectroscopy and measurements of S(Q,ω).
Robert McQueeney, 505-665-0841, mcqueeney@lanl.gov

NPDGamma building FP12 to be ready for:

commissioning run Fall 2002

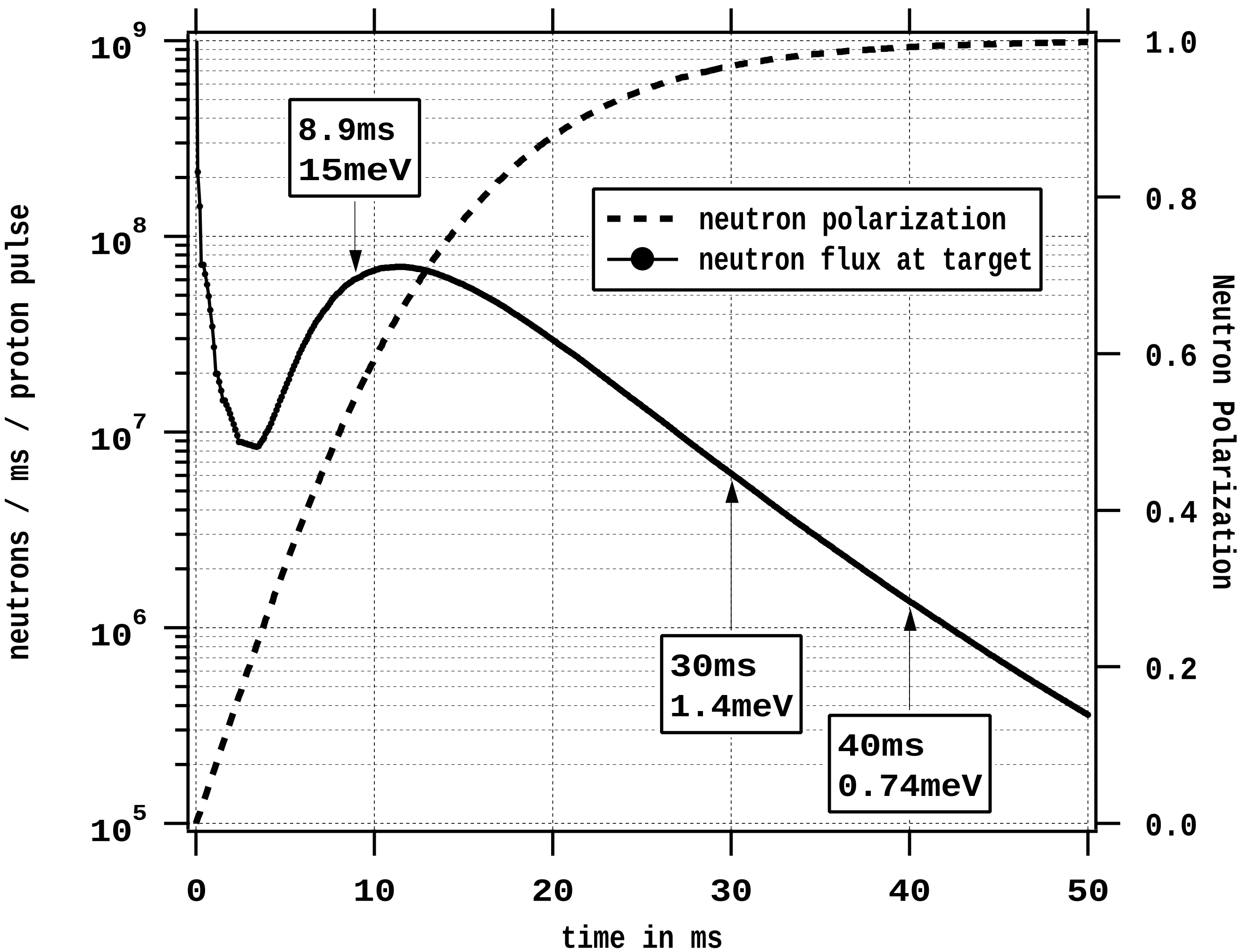
production data taking 2003



Pulsed beam: time of flight $\longrightarrow$ energy

Use energies 1.5 meV to 15 meV

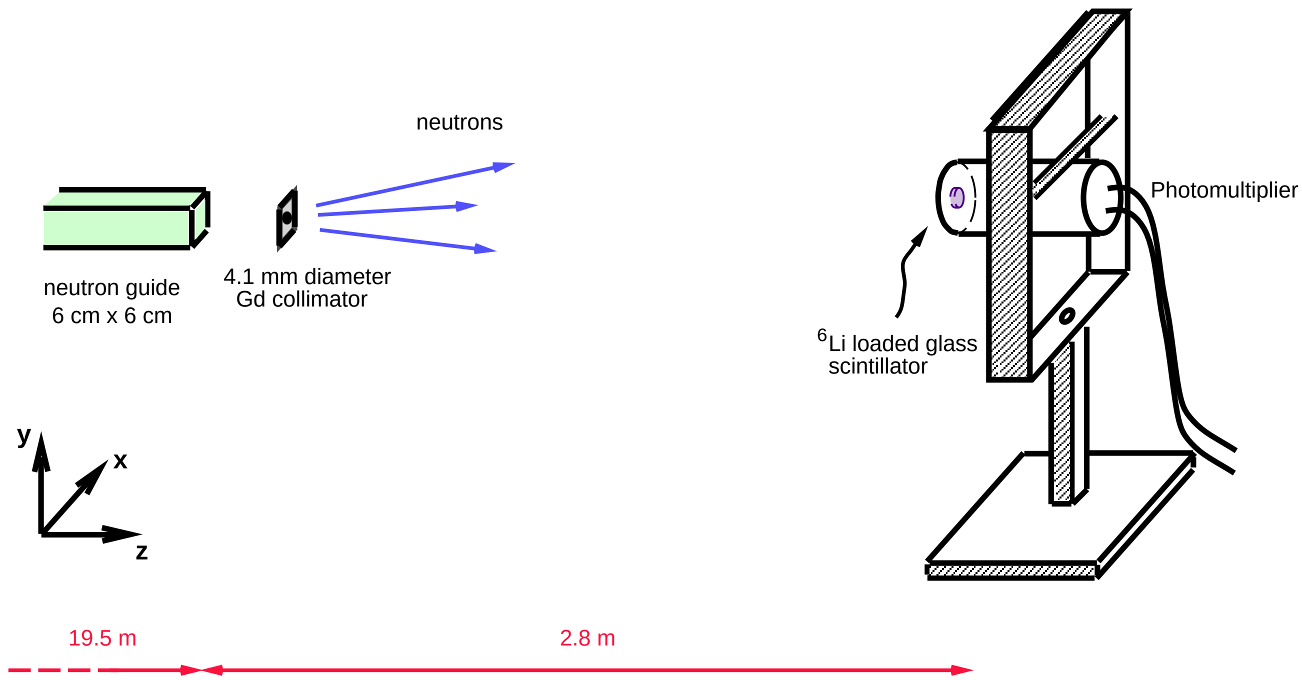
Monte Carlo calculation



PV asymmetry A_γ is independent of energy

Neutron Flux Measurement (FP11A, Fall 2000)

Measured the flux by collimating the beam and counting with a small detector on a movable stage



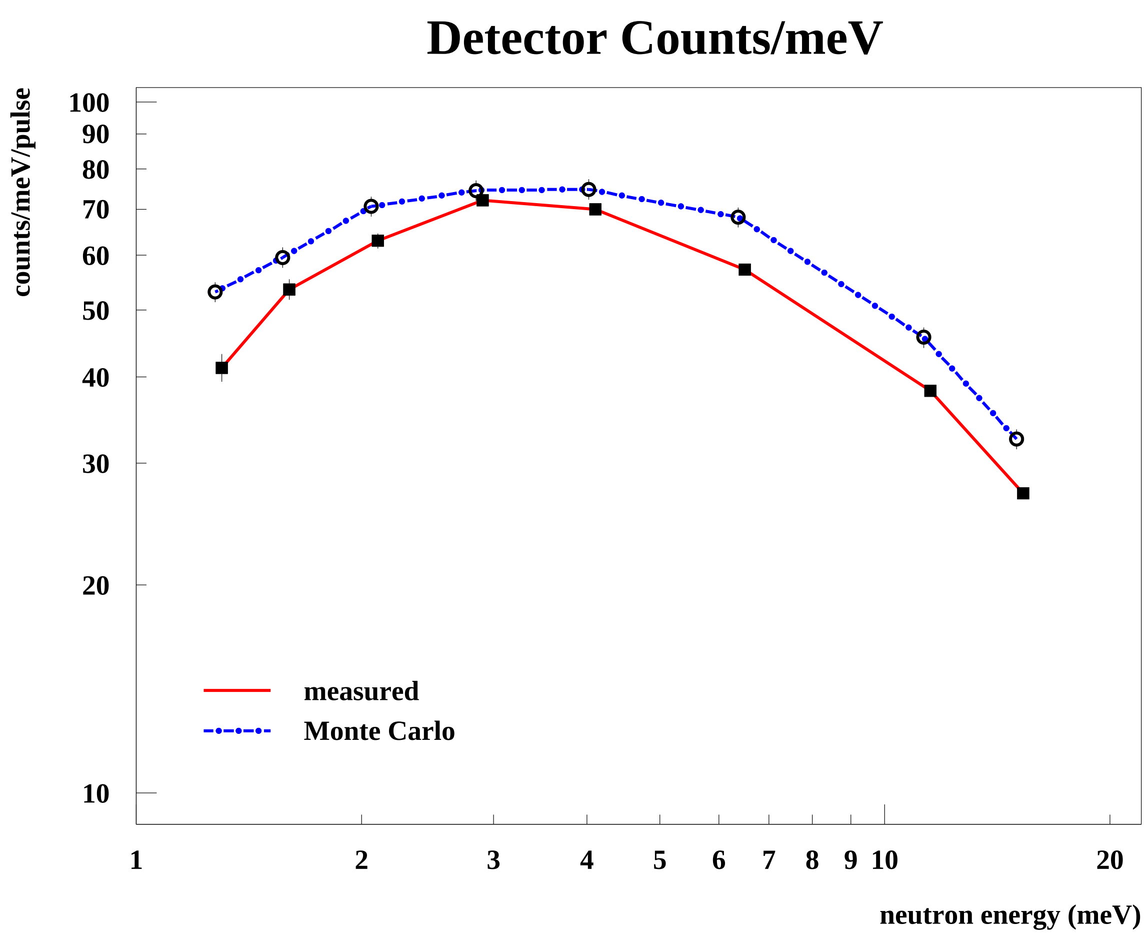
$$n + {}^{6}\text{Li} \rightarrow {}^{4}\text{He} + {}^{3}\text{H} + 4.78\ \text{MeV}$$

$$\sigma(\text{b}) = 149/\sqrt{\text{E(eV)}}$$

Compare measured flux to predicted flux for a partially coupled LH_2 moderator, using a Monte Carlo to calculate neutron guide transport and collimation effects for FP11A

Excellent agreement (20%)
with magnitude and E dependence

$\longrightarrow$ FP12 flux will be as assumed for NPDGamma
and have a demonstrated method to measure it

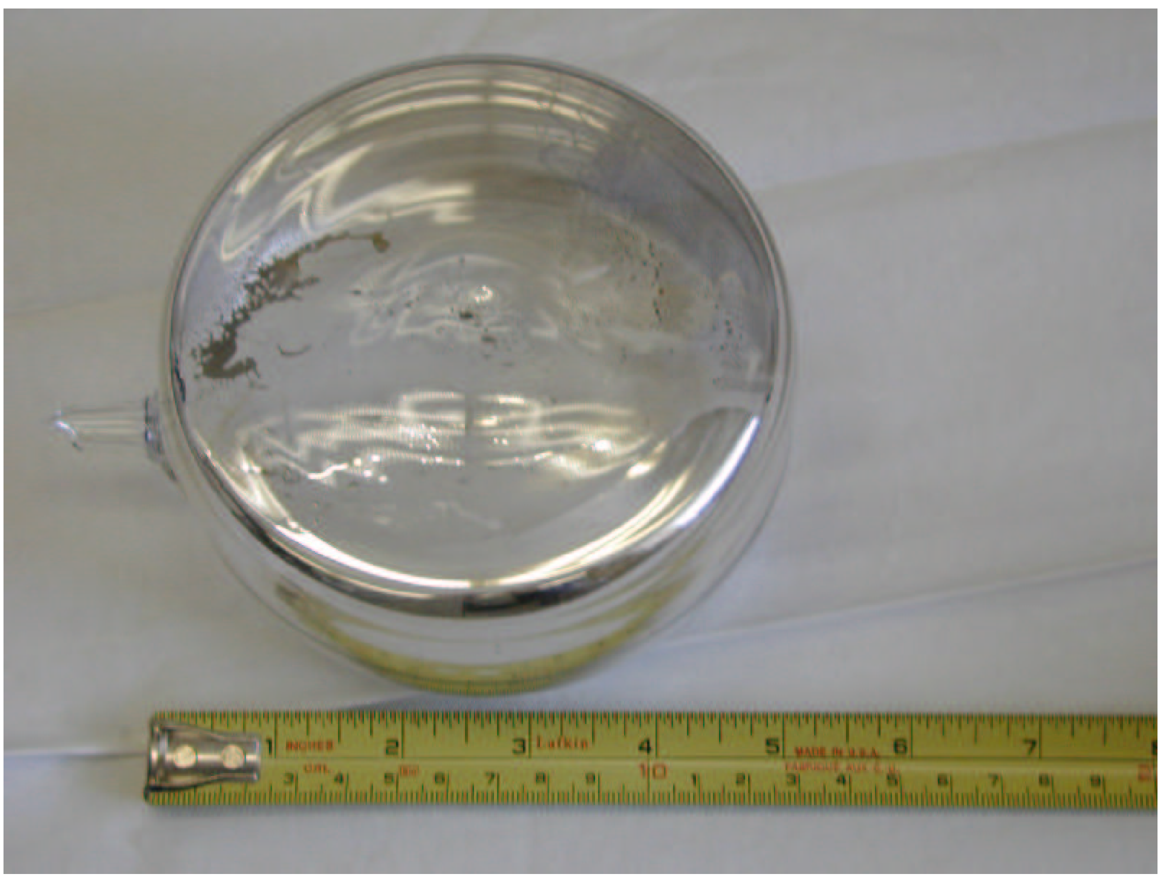


^{3}He Spin Filter

Optical pumping of Rb vapor $\rightarrow$
polarize ^{3}He by spin-exchange collisions ...

... then n polarized by passing beam through the cell. Antiparallel spin neutrons absorbed.

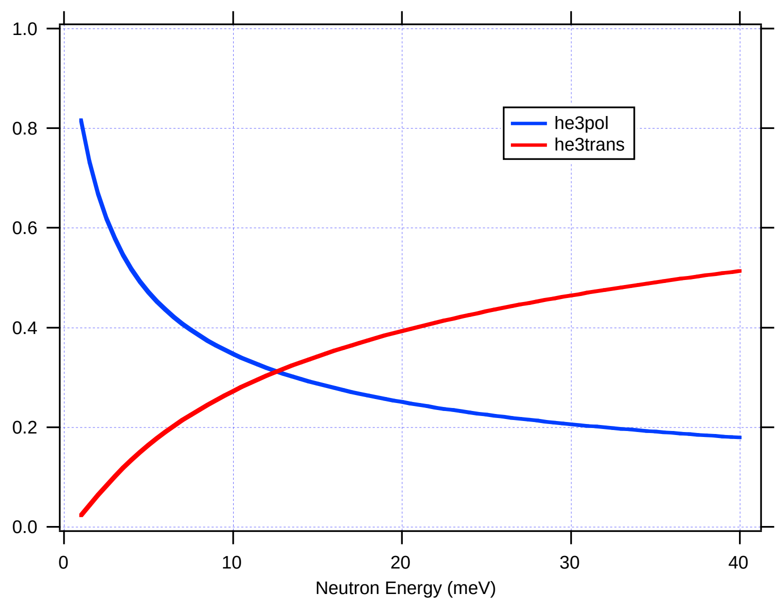
Fall 2000 Test Run:
^{3}He polarization of 26.5% $\rightarrow$
n polarization of 30-70% for 2-10 meV

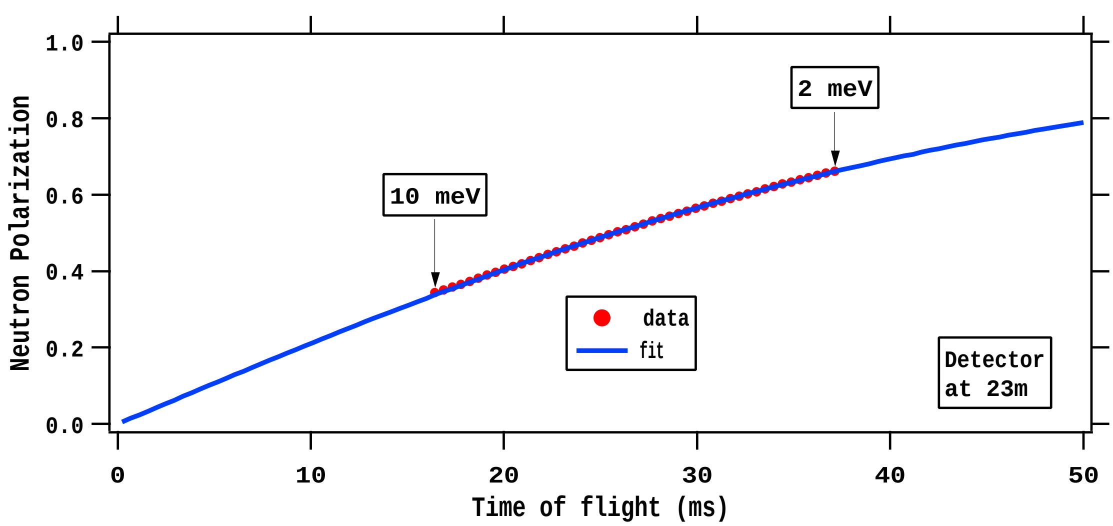


NIST group has fabricated large single cell:
12 cm dia., $T_1 > 500$ hr $\rightarrow$ 50% ^{3}He pol.

^{3}He system $\longrightarrow$ polarized neutron beam

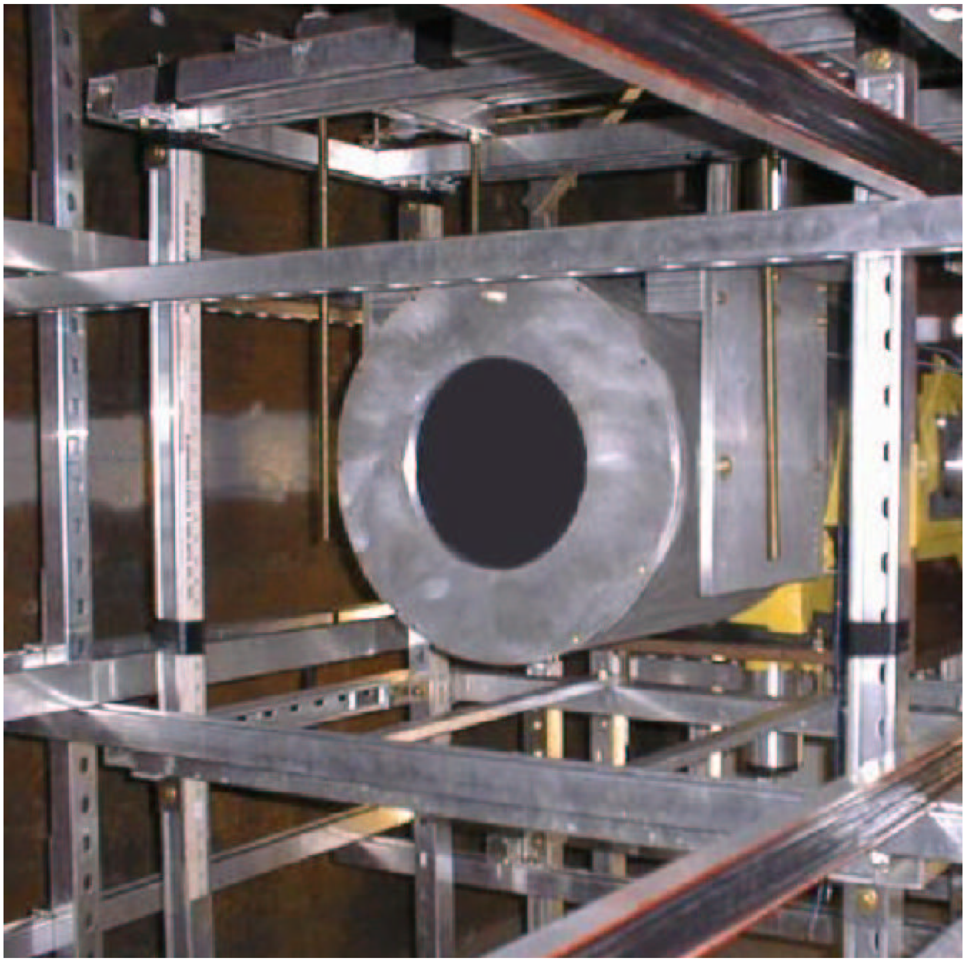
Transmission & polarization depend on neutron energy in a well-understood way

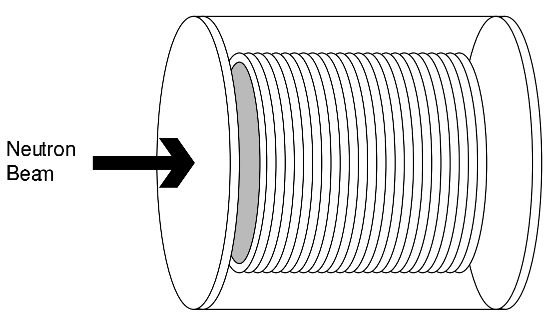


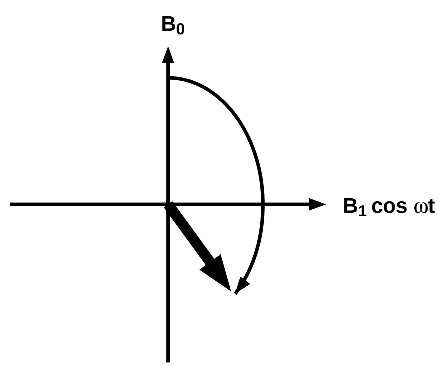


(Data from Fall 2000 Test Run)

Radio Frequency Spin Flipper

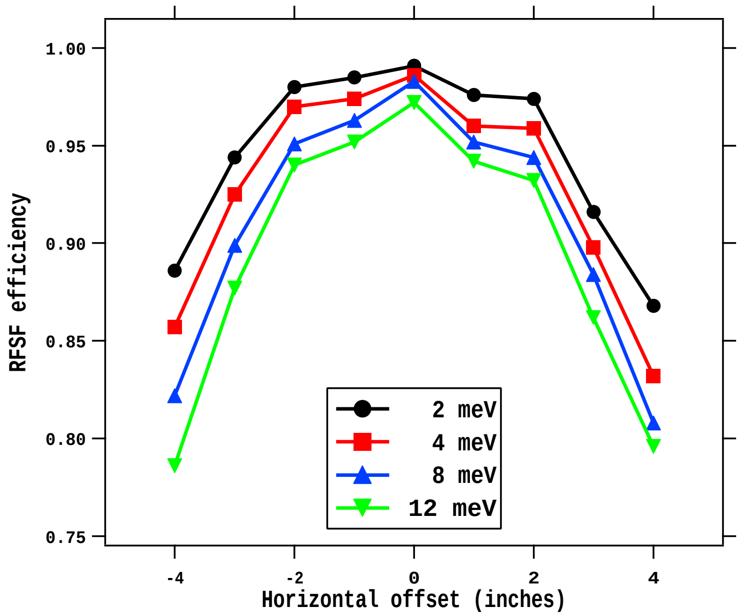


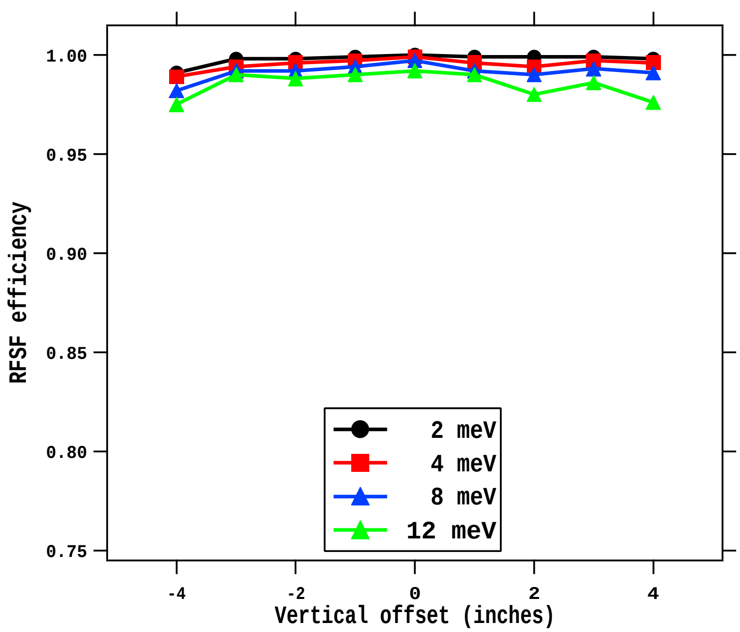




In a DC magnetic field, apply a resonant RF magnetic field to precess the neutron spin by π

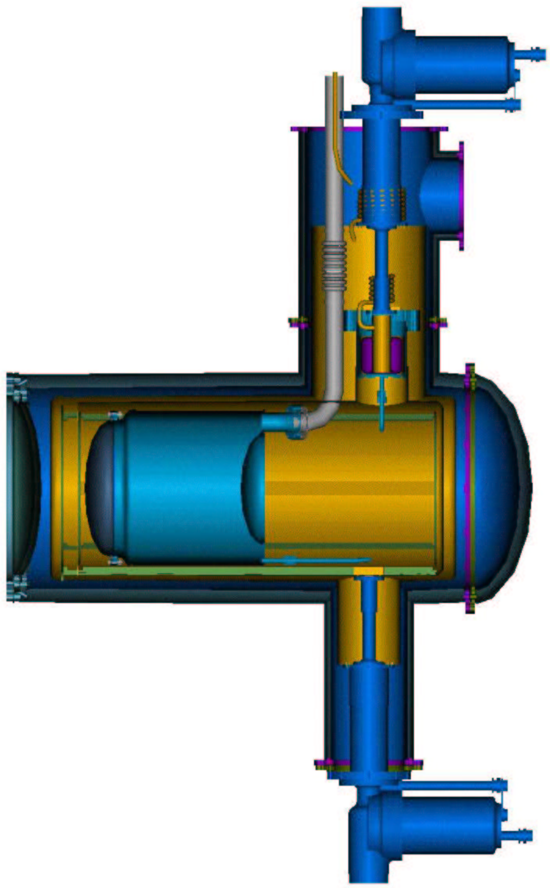
Spin flipper efficiency versus position
very good (>95% on axis)





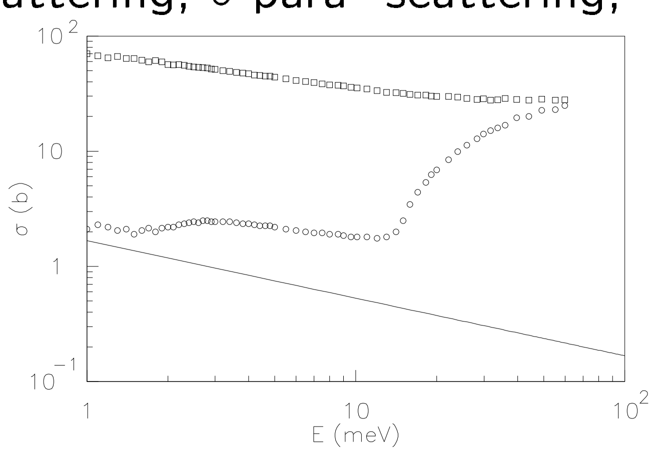
Liquid para-hydrogen target

20 ℓ, Mg-Al cryostat window, ^{6}Li liner



n cross-sections: ortho- ($\uparrow\uparrow$) and para- ($\downarrow\uparrow$) hydrogen

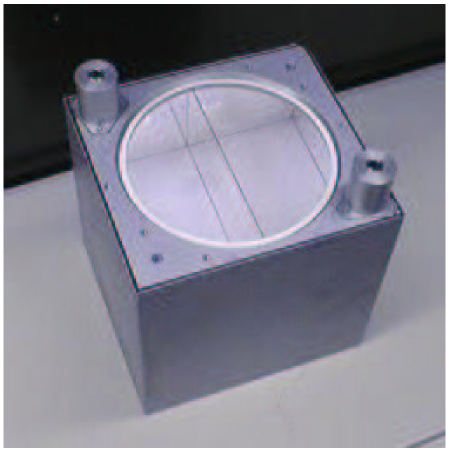
$\square$ ortho- scattering, $\circ$ para- scattering, $-$ np capture

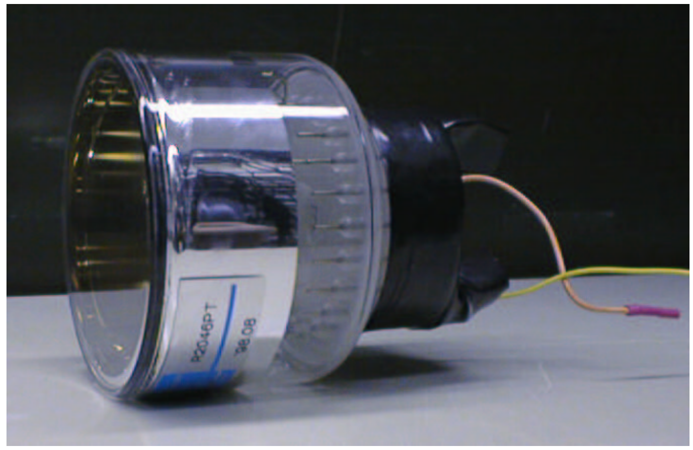


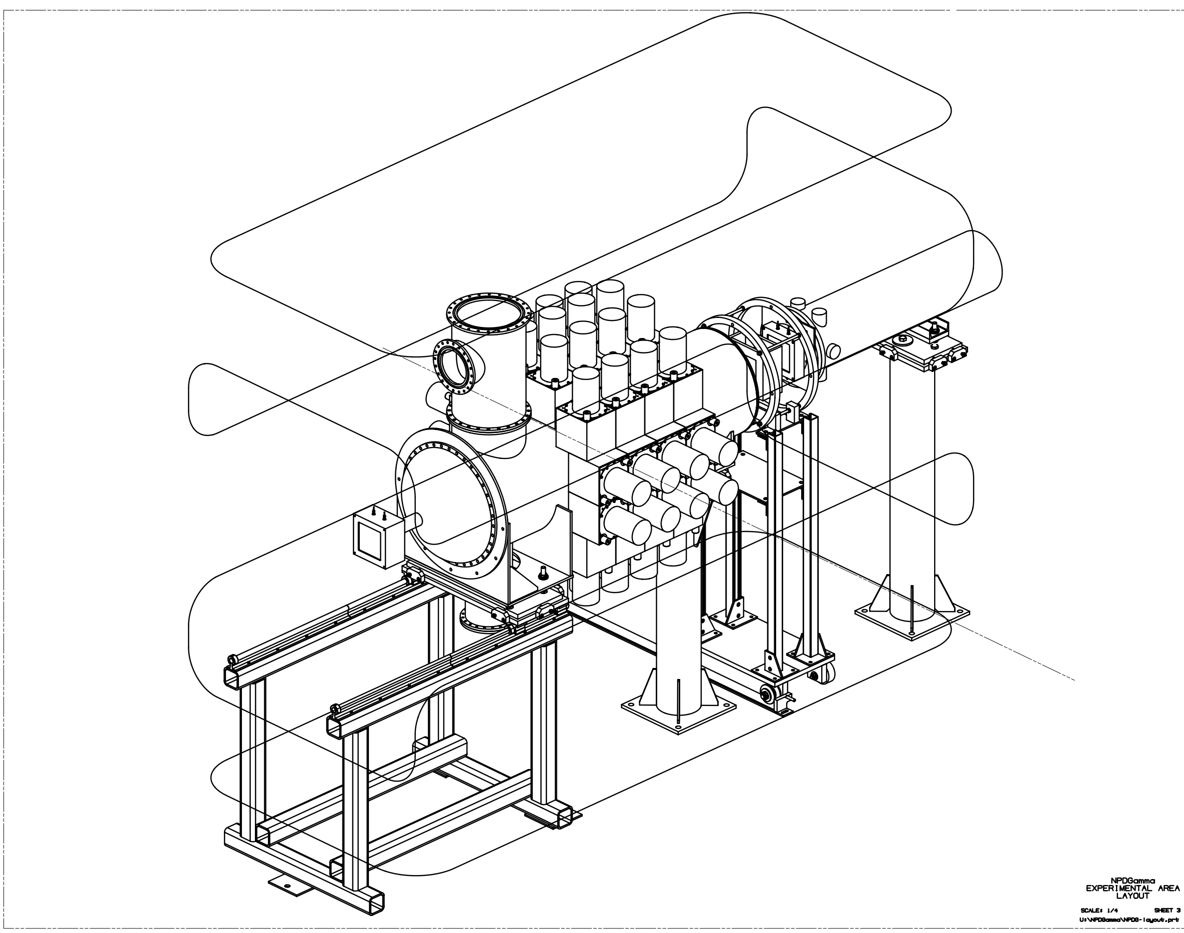
at 17K, ortho- fraction is 0.03%

CsI(Tl) and Photodiode γ Detectors

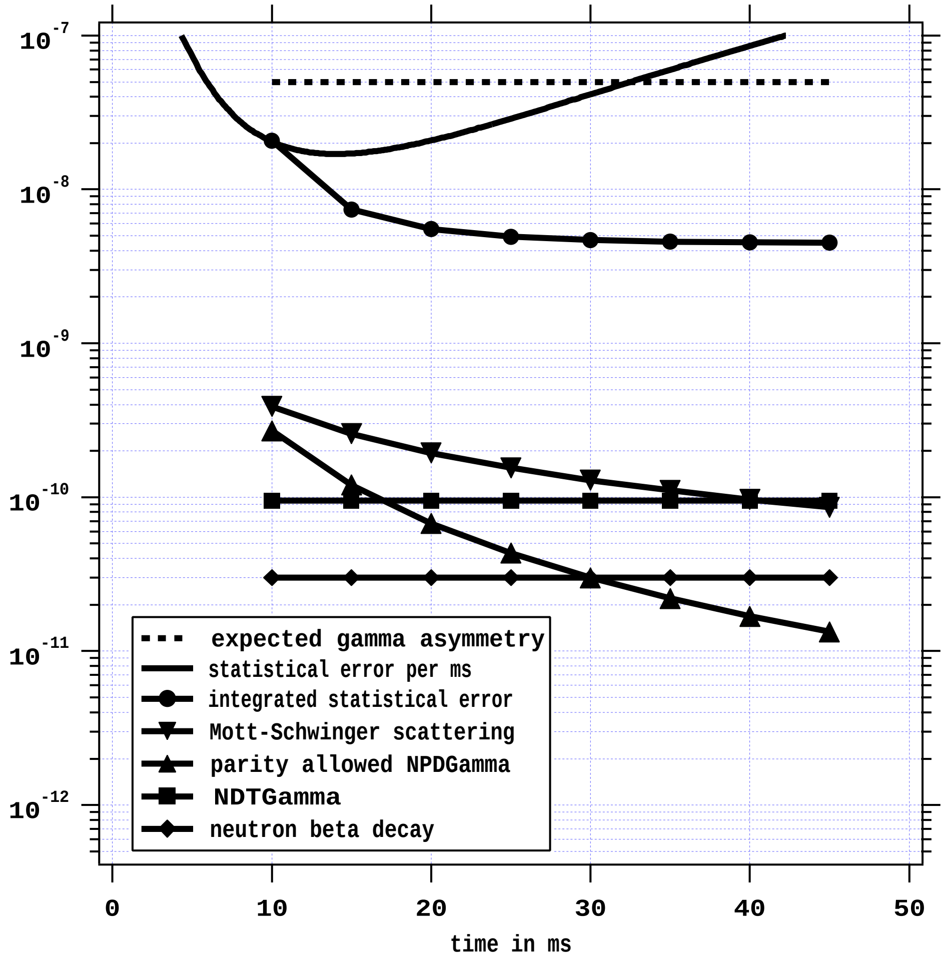
48 of these detectors will be used in the full experiment







NPDGamma Systematic Errors



Physics processes:

- activated materials (e. g. cryostat windows) emit γs in β-decay
- Stern-Gerlach steering
- L-R asymmetries:
  $n - p$ elastic scattering
  $n - p$ parity-allowed asymmetry
  Mott-Schwinger scattering (n spin-orbit interaction)

Instrumental issues: electronic noise, sensitivity to magnetic fields, gain stability over time

Null tests of E $>$ 15 meV and at end of each pulse

NPDGamma Fall 2000 Test Run

Lujan Center FP11A

- measured n flux to benchmark Monte Carlo

- verified n intensity fluctuations to be small

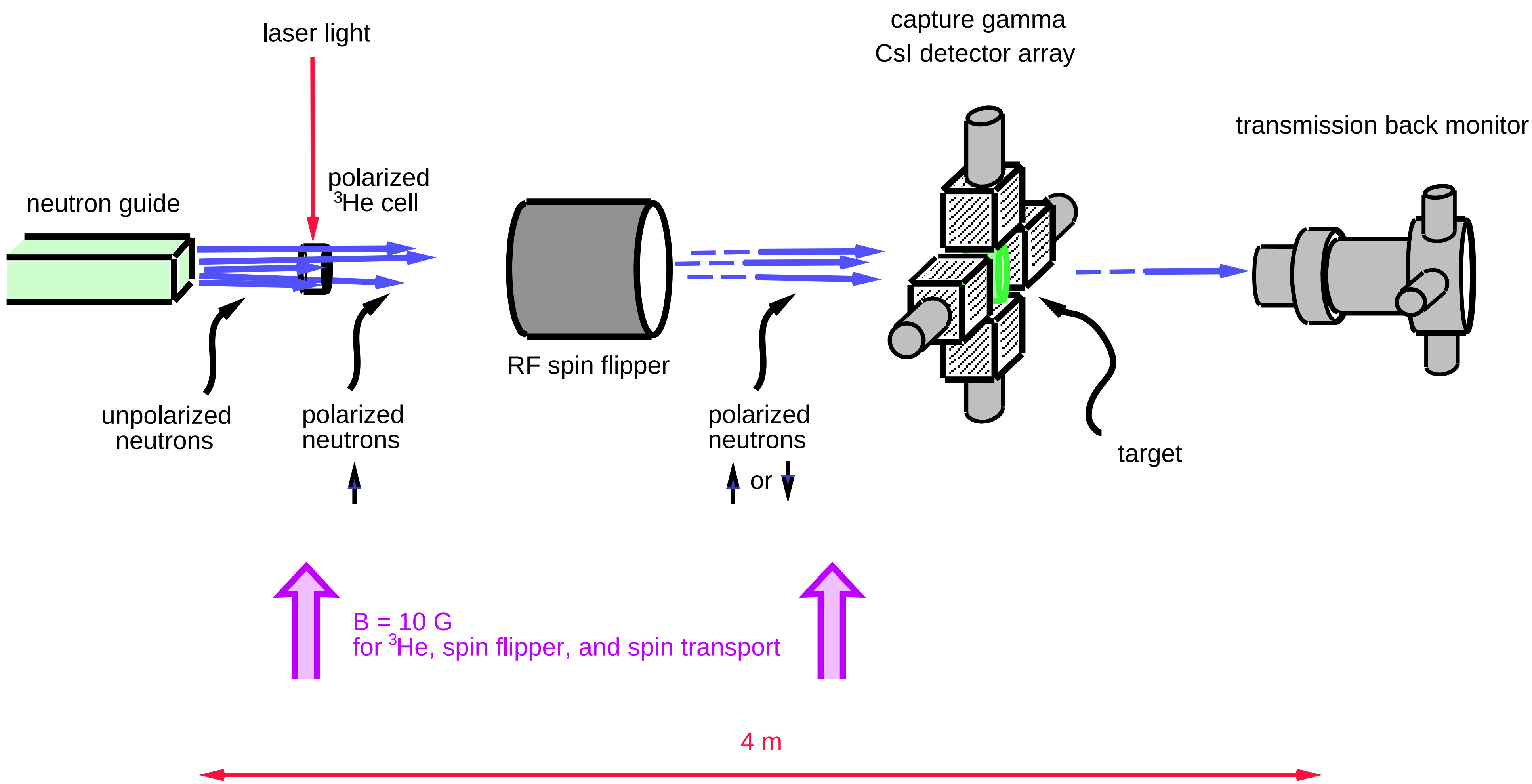
- polarized a neutron beam with a ^{3}He spin filter (thickness 6 atm·cm, $P \approx 26.5\%$)

- measured RF spin flipper efficiency ($> 95\%$) vs. energy and position

- used a new transmission back monitor (^{3}He/H_2) to observe beam intensity and measure RF spin flipper performance

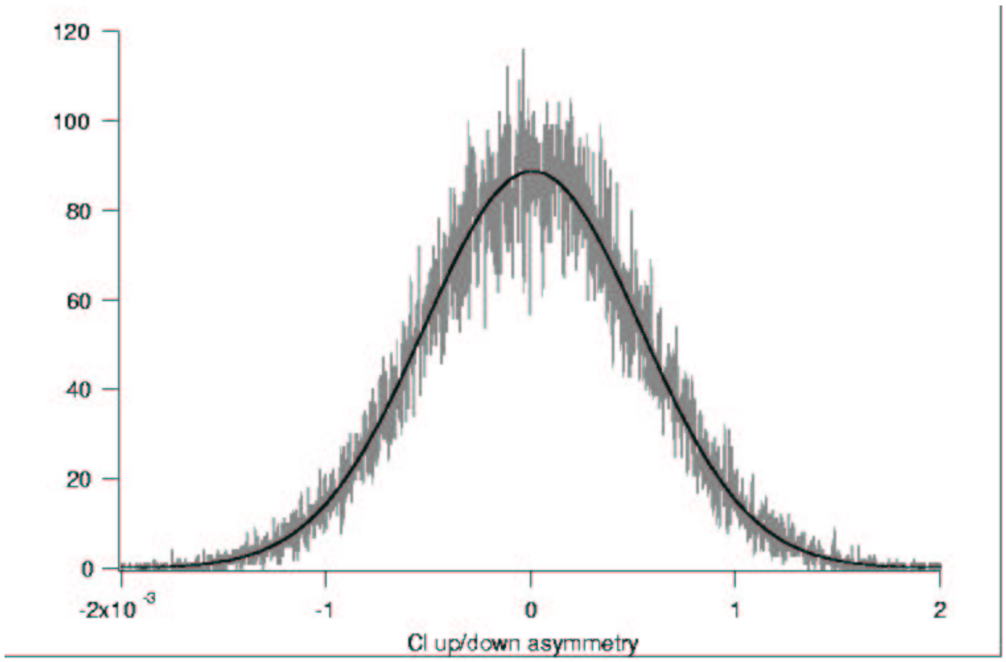
- measured PV neutron capture asymmetries in Cl, La, Cd, to $\pm 2.5 \times 10^{-6}$ (stat.), $\pm$few$\times 10^{-7}$ (syst.) in eight hours data taking per target, using four CsI(Tl) current mode γ detectors and 3" vacuum photodiodes, and VME-based DAQ system

Fall 2000 Engineering Run Setup



Asymmetry measurements on Cl, La, Cd

up/down $\rightarrow$ parity violating



Raw Asymmetries $\times 10^{-6}$

	PV $\vec{s}_n \cdot k_\gamma$	PC $\vec{s}_n \cdot (k_\gamma \times k_n)$
^{35}Cl	-7.68 ± 2.17	-2.14 ± 2.13
^{139}La	-5.88 ± 2.35	-0.20 ± 2.26
^{113}Cd	$+1.94 \pm 1.48$	-1.58 ± 1.45

Parity-conserving (left-right) $\vec{s}_n \cdot (k_\gamma \times k_n) \times 10^{-6}$

	^{35}Cl	^{113}Cd	^{139}La
Preliminary	-6.4 ± 6.4	-4.7 ± 4.6	-0.6 ± 6.6

Parity-violating (up-down) $\vec{s}_n \cdot k_\gamma \times 10^{-6}$

	^{35}Cl	^{113}Cd	^{139}La
BPKLNP	-27.8 ± 4.9	-1.3 ± 1.4	-17.8 ± 2.2
ILL	-21.2 ± 1.7	-	-
Preliminary	-23.1 ± 6.5	$+5.8 \pm 4.4$	-17.1 ± 6.8

NPDGamma Status

- FP12 flight path and experimental cave are under construction.

- Experiment is under construction.
  10% scale apparatus tested Fall 2000.
  Alignment scheme & monitors tested Fall 2001.
  All crucial components demonstrated.

- Test runs indicate design is sufficient for target A_γ experimental error, 0.5×10^{-8}.

- Potential systematic errors studied extensively.

- NPDGamma will make a clean measurement of H_π^1, the most fundamental weak N-N coupling.

NPDGamma Schedule

January 2002	Start beamline installation
Late Fall 2002	FP12 Commissioning Run
Early 2003	Install LH_2 target
July 2003	Commission entire experiment
Fall 2003	Begin data taking